

UNITED STATES PATENT APPLICATION FOR  
MOLECULAR MEMORY MEDIUM AND MOLECULAR MEMORY  
INTEGRATED CIRCUIT

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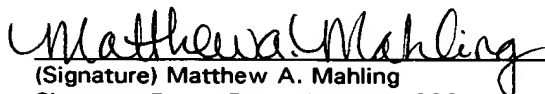
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This application claims the benefit of prior filed  
and co-pending United States Provisional Application  
*Culver et al.*, entitled "Molecular Memory Medium and  
Molecular Memory Integrated Circuit," and having a  
15 series/serial no. of 60/112,787.

Background of the Invention

Field of the Invention

20

This invention relates to memory reading and  
writing apparatus. The invention is more particularly  
related to memory reading and writing apparatus that  
utilize operations on single atoms or molecules, and

groups of atoms or molecules for performing memory reading and writing.

References

5           This application incorporates by reference, in their entirety, the following documents:

- (1)           U.S. Patent 5,453,970, (Rust et al.)
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- (12) Large-scale charge storage by scanning capacitance microscopy, R.C. Barrett and C.F. Quate, Ultramicroscopy 42-44 (1992) p. 262
- 5 (13) High Density data storage using proximal probe techniques, The IBM Journal of Research and Development, Volume 39, #6, Nov. 1995.
- (14) Disk/Trends, private conversation with Jim Porter, August, 1996
- 10 (15) Submicron Studies of Recording Media Using Thin-Film Magnetic Scanning Probes, advance copy to appear in Applied Physics letters, 4/95
- (16) Atomic Force Microscope-base Data Storage: Track Servo and Wear Study, IBM Almaden Research Center, presented STM 97.
- 15 (17) U.S. Patents 5,216,631, and 5,307,311 (Silwa, Jr.)

Discussion of the Background

20 Current technology for high density solid state memory employ various means for storing and reading data.

A summary of previous patent applications in this area are listed in U.S. Patent No. 5,453,970, entitled

"Molecular Memory Medium and Molecular Memory Disk Drive for Storing Information Using a Tunneling Probe" by Thomas F. Rust and Joanne P. Culver.

Current technologies using movement of atoms and molecules (molecular scale technologies) are not practical because my problems exist regarding the efficient reading, writing (including maintaining a high density of storage) on media materials. Further problems with current devices include structures that are difficult or impossible to build using existing tools.

SUMMARY OF THE INVENTION

Accordingly, the present invention provides a device capable of reading and/or writing on a substrate by affecting (via movement of molecules/atoms, and/or modification of electrical properties (including any of charges, resistance, capacitance, inductance, and magnetic properties) stored on the media.

The present invention includes a media prepared for storage of data bits in a high density via movement of molecules/atoms on the media and/or the modification of electrical properties on the media.

The present invention, in it's various embodiments, has many distinguishing features, for example:

1) The present invention utilizes multiple tips on  
5 each moving platform surface, where there are multiple  
surfaces are each movable independently.

2) The present invention memory operation does not  
rely on tunneling mode only.

3) The present invention does not rely on sharing  
10 Z actuators.

4) The present invention overcomes problems  
associated with the fact that the media surface is very  
difficult to form atomically flat ( $<1$  Angstrom) over a  
usefully large area, and that tunneling current is  
15 useful only under approximately 10 Angstrom.

5) The present invention does not rely on multiple  
resonating columns operating in perfect synchrony. A  
problem associated with synchrony of resonating columns  
is that small differences in size cause a column to  
20 resonate at a slightly different frequency. The phase  
is also very sensitive to sub-harmonic distortion.  
Even a slight change would mean a large phase  
difference would quickly appear between columns.

Manufacturing difficulties arise in manufacturing columns exactly identical.

6) Most molecular media have occasional large particle defects. These defects, when swinging past  
5 the tips would destroy the tips. Either the tip or the media is in constant lateral motion, making such defects difficult to avoid. Provided herein is a method and device to overcome these problems.

7) The present invention utilizes platforms of  
10 very low mass. As a result, the present invention provides fast access speed.

A molecular memory integrated circuit (IC) is a device for storing very large quantities of information, and is also uniquely capable of providing  
15 very high data rates of this information to and from the IC. The molecular memory IC may be manufactured at a cost comparable to current ICs, yet at a fraction of the cost required to achieve the same amount of storage. The molecular memory IC may substitute for  
20 many devices which currently are used as a storage medium. The molecular memory IC may be used to replace disk drives in computer systems, the magnetic tape systems in video and audio tape recorders, photographic film used for information storage, and even EEPROM



(electrically erasable read only memory), VRAM (video random access memory) and DRAM (dynamic random access memory) where access time is not a high priority. Data transfer rates will depend on the architecture used in the IC, and may involve trade offs between overall memory capacity versus maximum latency. A typical molecular memory IC of  $1.6 \text{ cm}^2$  will store over 860 Megabytes of data. The molecular IC may replace magnetic tape in camcorders, digital and analog audio tape, video tape, and CD-ROM players. In one embodiment, the present invention has been fabricated using a laser ablated diamond media to produce a Molecular Array Read/write Engine (MARE) IC with the following specifications:

- Given:
- Domain spacing .030 microns.
  - Compaction function ratio 1.15 using honeycomb data structure
  - Space utilization 22:1 (ratio of total area of IC to usable media)

Then:

Number of bits per square centimeter = 111 billion.

Maximum latency to access any bit is 500 microsec.

Total capacity of 1.2 square centimeter IC is 860 Megabyte.

45 Platforms with 12 read/write heads per platform -  
5 total of 540 heads

Scan rate 90KHz per bit/tip.

Platform thickness 4 micron, platform and actuator cell  
size 1900u x 1400u

6 Mbyte/sec data transfer rate

10

In accordance with the present invention, there is provided a memory apparatus comprising an input section which comprises one or more fine tip portions, a control means for controlling the input section,  
15 whereby high density recording is achieved, an output section, comprising a similar or identical fine tips, and fixed or moving substrate surface or surfaces, comprising sets of molecules, atoms, electrons, or the void left by sets of molecules, atoms, or electrons the  
20 position of each set or void or orientation of molecules, atoms, or electrons defining the states of memory regions.

In an alternate embodiment, there is provided a memory apparatus comprising an input section which

comprises a source of fine electromagnetic radiation and/or a fine tip, a control means for controlling the input section, whereby high density recording is achieved, an output section, comprising a fine tip  
5 and/or electromagnetic radiation sensitive receptor, and fixed or moving substrate surface or surfaces, comprising sets of molecules, atoms, or electrons, or the void left by sets of molecules, atoms, or electrons the position of each set or void of molecules, atoms,  
10 or electrons defining the states of memory regions. Magneto-optic effects are also contemplated.

In an alternate embodiment, there is provided a memory apparatus comprising an input section which comprises a fine tip with a ferromagnetic coating, a  
15 control means for controlling the input section, whereby high density recording is achieved, an output section, comprising a fine tip with a sensitive magnetic receptor, and fixed or moving substrate surface or surfaces, comprising sets of magnetic  
20 domains the position of each set or void of domains defining the states of memory regions.

Generally, the recording of information is performed by the addition, removal or repositioning of atoms, molecules, electrons or magnetic domains from

the region either immediately above, on, or immediately below the surface of the molecular media. The removal or repositioning force is either a mechanical force, chemical reaction (as in chemical bond interactions, catalyst, etc.), electrostatic force, electromagnetic radiation, DC or AC magnetic field, electric current, or thermal force. A combination of these above forces come into play to perform writing on the molecular media. The reading of information is performed by one of the methods of one of or a combination of:

- a) analyzing patterns of current (field emissive, tunneling, or purely resistive) between a fine tip and the surface of the molecular media,
- b) analyzing patterns of electromagnetic radiation through a receptor received from the surface of the molecular media in response to a stimulus,
- c) analyzing patterns of shifting phase in a vibrating tip,
- d) analyzing patterns of changing amplitude of a vibrating tip,
- e) analyzing patterns of current and/or voltage between a fine tip and the surface of the molecular media which vary over time during the reading of each bit, in conjunction with topological information

concerning the media surface computed dynamically, to provide very high speed access to the information stored.

One of the techniques for re-write capability  
5 involves re-planing of the memory surface, to effect more than a write-once capability.

The medium of a molecular memory surface can be any one of a large class of materials. The present invention describes a number of different materials,  
10 and several different techniques for reading and writing the materials. The present invention allows for a large class of materials to be used as the memory surface by virtue of the ability of the read/write head to fly above a relatively uneven surface at very high  
15 speeds, and the large range of forces with which to read and write information.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a molecular memory integrated circuit  
20 apparatus according to the present invention utilizing four moving platforms each containing 8 fine tips and a single memory surface (positioned over the IC with the media facing down - not shown);

FIG. 2 shows an enlarged view of one of the platforms with the springs, electrostatic actuators, electronics, and 8 fine tip assemblies;

FIG. 3 is an enlarged view of one of the  
5 spring/actuator assemblies;

FIG. 4 is an enlarged view of one of the fine tip assemblies with the Z actuator;

FIG. 5 is an enlarged view of an alternate spring actuator assembly;

10 FIG. 6 shows an alternate molecular memory integrated circuit apparatus according to the present invention utilizing four moving platforms each containing 12 fine tips and a single memory surface (positioned over the IC with the media facing down -  
15 not shown);

FIG. 7 is an enlarged view of an attraction mode alternate spring actuator assembly;

FIG. 8 is an enlarged view of an alternate attraction mode alternate spring actuator assembly with  
20 short actuation in the Y axis and long spring movement in the X axis;

FIG. 9 is an enlarged view of an alternate Z actuator using electrostatic attraction with capacitive position sensor;

FIG. 10 is an enlarged view of an alternate Z actuator using electrostatic attraction;

FIG. 11 is an enlarged view of a complete set of 12 Z actuators from Fig. 9, and a pair of actuators  
5 from Figs. 7 and 8, with interconnects;

FIG. 12 is an enlarged view of a thermal bimorph actuator with extra conductor;

FIG. 13 is a cross section of the actuator portion of the electrostatic Z actuator from Fig. 9;

10 FIG. 14 is a cross section of the actuator portion of the electrostatic actuators 7 and 8;

FIG. 15 is a cross section of a thermal bimorph actuator with extra conductor;

15 FIG. 16 is an enlarged view of a complete set of 6 Z actuators from Fig. 9, and a pair of actuators from Figs. 7 and 8, with interconnects, designed for use with the rotating disk memory;

FIG. 17 is an enlarged view of 4 devices from Fig. 16 arrayed around a rotating disk memory;

20 FIG. 18 is an enlarged cross section view of an amplifying memory media;

FIG. 19 is an enlarged view of three states of an amplifying memory media;

FIG. 20 is an enlarged view of an STM image of a bit formed on doped diamond;

FIG. 21 is three views of thin film multi-layers before processing to reduce stress bias;

5        FIG. 22 is three views of thin film multi-layers after processing to reduce stress bias;

FIG. 23 is an enlarged view of an electro-magnetic radiation emitter and electromagnetic radiation receptor with media;

10       FIG. 24 is an enlarged view of an electro-magnetic radiation emitter and electromagnetic radiation receptor with media and a particle, showing shadow paths;

15       FIG. 25 is an enlarged view of the states of a nitride on silicon memory media;

FIG. 26 is an enlarged view of the states of an insulator on silicon memory media;

FIG. 27 is an enlarged view of a regular rectangular data storage scheme;

20       FIG. 28 is an enlarged view of a honeycomb data storage scheme;

FIG. 29 is an enlarged view of a corner of an array of actuators from Fig. 16 designed with row and column controls and input/output;



FIG. 30 is an enlarged view of one cell of a molecular array read/write engine with a chevron electrostatic X and Y actuators, and 12 sets of assemblies consisting of electrostatically operated Z  
5 actuators with cantilevers, heads with fine tips, position sensors, read/write coils and 8 spacing nub assemblies integrated on one platform, with connecting wires;

FIG. 31 is an enlarged view of the area around a  
10 tip from Fig. 30;

FIG. 32 is an enlarged area of the Z actuator from Fig. 30;

FIG. 33 is an enlarged area of the tip from Fig. 31;

FIG. 34A is an enlarged area of the X actuator  
15 from Fig. 30;

FIG. 34B is a cross section of one arm area of the X actuator from Fig. 30;

FIG. 35 is an enlarged view of several cells of a  
20 molecular array read/write engine with an enhanced electrostatic comb X and Y actuators, and 12 sets of assemblies consisting of electrostatically operated Z actuators with cantilevers, heads with fine tips, position sensors, read/write coils and 8 spacing nub

assemblies integrated on one platform, with connecting wires;

FIG. 35B is an enlarged area of the X actuator from Fig. 35;

5        FIG. 35C is an enlarged area of the comb fingers of the X actuator from Fig. 35B;

FIG. 36 is an enlarged area of a thermal X actuator with capacitance sensor;

10       FIG. 36B is an enlarged area of the X actuator from Fig. 36;

FIG. 36C is a cross section of one of the X actuators from Fig. 36;

FIG. 37 is an enlarged area of the Z actuator from Fig. 30;

15       FIG. 38 is an enlarged area of one cell of a molecular array read/write engine with a thermal 2 stage series, 4 stage parallel X and Y actuators, and 10 sets of assemblies consisting of thermally operated Z actuators with cantilevers, heads with fine tips,  
20       piezoresistive Z position sensors, 4 spacing nub assemblies integrated on one platform, with connecting wires;

FIG. 39 is an enlarged area of one cell of a XY movable media with servo grid alignment marks with a

thermal 2 stage series, 4 stage parallel X and Y actuators, 4 spacer bearing plates integrated on one platform, with connecting wires to each media substrate;

5           FIG. 40 is an enlarged area of a thermally operated Z actuator with cantilever, conductive head with fine conductive tip, piezoresistive Z position sensor and thermal heater element;

10           FIG. 41 is an enlarged diagrammatic view of one cell of a molecular array read/write engine with X and Y actuators/springs, and 12 sets of assemblies consisting of Z actuators with cantilevers, conductive heads with fine conductive tips, Z position sensors, movable media consisting of X and Y actuators/springs,  
15           and media (shown transparent for clarity);

FIG. 42A is view from an atomic force microscope using a conductive tip operated at resonance showing 3 bits written in NO charge storage media with 30-60 nm domains (X and Y axis not same scale);

20           FIG. 42B is same region from 42A with center bit erased using reverse polarity pulse;

FIG. 42C is a higher magnification view of a written charge storage bit;

FIG. 42D is a view of region in Fig. 42C after erasure;

FIG. 42E is a view of region in 42D after re-writing;

5        FIG. 43 is an example of sync bits maintained in tracks of a media material;

FIG. 44 is an example of a fine tip acquiring the media, and data;

10       FIG. 45 is an example of a track and sector layout of a media material;

FIG. 46 is an example of a media material constructed with capacitive wells for increasing an amount of charge stored in the media;

15       FIG. 47 is an example structure of thermally activated cantilever having an embedded piezo electric sensor for detecting an amount of movement of the cantilever;

FIG. 48 is an example of an amplifying media;

20       FIG. 49 is an enlarged view of the amplifying media of Fig. 48; and

FIG. 50 is a block diagram of example control devices interfacing with the media/platform, cantilevers, and tips.

Detailed Description of the Invention

According to the present invention, a molecular memory integrated circuit apparatus comprises one or more stacked systems each comprising a memory element  
5 comprising one or more media surfaces, optional servo tracking marks embedded in the media surface, a positioning mechanism for positioning the media surfaces, a control means for controlling the positioning mechanism, an input/output section which  
10 comprises at least one head having a fine tip portion faced towards the memory media surface, a positioning mechanism for positioning the head or heads above the memory media surface or surfaces, a control means for controlling the positioning mechanism, a write section  
15 which converts an analog or digital signal to write information, a sense section which converts the input section to analog or digital information, an optional sense section which converts position information to analog or digital information, an optional cleaning  
20 section which removes unwanted particles, an optional sharpening area where unwanted particles are removed and/or added to the tip, and a fine tip alignment section.

The control section comprises means for bringing the tip portion of the head close to the surface of the memory media to thereby effect positioning, means for allowing the tip portion to scan the memory, means for  
5 controlling the distance between the tip and the memory media during scanning, and means for positioning the tip at, above, or below the surface of the memory media. The head or heads have a fine tip portion attached to an oscillating mechanism operating at or  
10 near a resonant peak such that when the tip is operated near the memory surface, the phase of the oscillation shifts from its free space value. The amount of this phase shift increases as the distance between the memory and the tip at its closest position to the media  
15 decreases. In addition, the state of data bits under the tip may shift the phase of the oscillation above or below the free space value.

#### **DESCRIPTION OF THE TUNNELING MODE ALTERNATE EMBODIMENTS**

20 According to the present invention, a molecular memory integrated circuit apparatus comprises a memory element comprising one or more media surfaces, an input/output section which comprises at least one head having a fine tip portion faced towards the memory

media surface, a positioning mechanism for positioning the head or heads above the memory media surface, a control means for controlling the positioning mechanism, a sense section which converts the input  
5 section to analog or digital information, an optional cleaning section which removes unwanted particles, an optional sharpening area where unwanted particles are removed and/or added to the tip, and a fine tip alignment section.

10 The control section comprises means for bringing the tip portion of the head close to the surface of the memory media to thereby effect positioning, means for allowing the tip portion to scan the memory, means for controlling the distance between the tip and the memory  
15 media during scanning, and means for positioning the tip at, above, or below the surface of the memory media. The head or heads have a fine tip portion such that a current flows between the tip portion and the memory surface. The amount of this current indicates  
20 the distance between the memory and the tip.

#### DESCRIPTION OF FORCE MODE ALTERNATE EMBODIMENTS

According to the present invention, a molecular memory integrated circuit apparatus comprises a memory

element comprising one or more media surfaces, an  
input/output section which comprises at least one head  
having a fine tip portion faced towards the memory  
media surface, a positioning mechanism for positioning  
5 the head or heads above the memory media surface, a  
control means for controlling the positioning  
mechanism, a sense section which converts the input  
section to analog or digital information, an optional  
cleaning section which removes unwanted particles, an  
10 optional sharpening area where unwanted particles are  
removed and/or added to the tip, and a fine tip  
alignment section.

The control section comprises means for bringing  
the tip portion of the head close to the surface of the  
15 memory media to thereby effect positioning, means for  
allowing the tip portion to scan the memory, means for  
controlling the distance between the tip and the memory  
media during scanning, and means for positioning the  
tip at, above, or below the surface of the memory  
20 media. The head or heads have a fine tip portion which  
is attached to a cantilever. This cantilever may be  
vibrating above or such that the tip slightly touches  
the surface, or the tip may be placed directly on the  
media surface. The cantilever is connected to a Z axis



drive mechanism which is electrostatic and capacitive, or may have a separate capacitive sensor for the Z axis. In the vibrating mode, the change in phase of the resonance of the vibrating cantilever indicates  
5 the tip is touching or near the memory surface. In the dragging mode, the deflection of the cantilever by the surface changes the capacitance of the drive electrodes, indicating position.

It is important to note here that individual parts  
10 of any of the embodiments described herein may be interchanged to produce a molecular memory device according to the present invention.

15 **DESCRIPTION OF AN ELECTROMAGNETIC RADIATION SOURCE/RECEPTOR ALTERNATE EMBODIMENT**

Figure 23 shows a cross section of the head portion of this embodiment. According to the present invention, a molecular memory integrated circuit  
20 apparatus comprises a memory element comprising one or more media surfaces 2300, an input/output section which comprises at least one fine electromagnetic radiation generating source 2310 and/or electro-magnetic radiation receptor 2320 (hereafter referred to as head)  
25 faced towards the memory media surface, a positioning mechanism for positioning the head above the memory

media surface, a control means for controlling the positioning mechanism, a sense section which converts the input section to analog or digital information, a cleaning section which removes unwanted particles, a sharpening area where unwanted particles are removed and/or added to the tip, and a fine tip alignment section. The electromagnetic radiation sources and receptors in this diagram may be reversed.

The control section comprises means for bringing the head close to the surface of the memory media to thereby effect positioning, means for allowing the head to scan the memory, means for controlling the distance between the head and the memory media during scanning, and means for positioning the head above the surface of the memory media.

#### **ELECTROMAGNETIC RADIATION SOURCE AS FINE TIP**

In one version, the electromagnetic radiation sources 2320 consists of a source such as a light emitting diode or LASER 2330 which may pass through a polarizing film 2340, then is piped through the waveguide structure consisting of materials 2350, 2360 and optionally 2370. The waveguide focuses the electromagnetic radiation to a fine tip portion 2355

such that a narrow beam emanates from the tip portion, impinges on the memory element 2305, and a modulated version of the electromagnetic radiation, the return electromagnetic radiation, emanates from the memory  
5 element. Some versions of the memory media modifies the electromagnetic radiation by altering the polarization of the electromagnetic radiation, such as with magneto-optic materials. The return electromagnetic radiation may again pass through a  
10 filtering polarization film 2390 and is then sensed by an electromagnetic radiation receptor such as a photodiode 2380. In some versions one or more of the materials 2350,2360,2370, may be conductive and the tip used in a tunneling mode for sensing, and/or the tip  
15 used to modify the memory element using any of the memory modification techniques which use such a tip. The use of the electromagnetic radiation may then be used as a sensor to read the media.

20 **ELECTROMAGNETIC RADIATION RECEPTOR AS FINE TIP**

In another version, the electromagnetic radiation source 2310 consists of a source such as a light emitting diode or LASER 2380 which may pass through a polarizing film 2390, and emanates as a broad beam.

The beam impinges on the memory element 2305, and a modulated version of the electromagnetic radiation, the return electromagnetic radiation, emanates from the memory element. Some versions of the memory media  
5 modifies the electromagnetic radiation by altering the polarization of the electromagnetic radiation, such as with magneto-optic materials. The return electromagnetic radiation is piped through the waveguide structure consisting of materials 2350, 2360  
10 and optionally 2370. The wave-guide directs the electromagnetic radiation through an optional filtering polarization film 2340 and is then sensed by an electromagnetic radiation receptor such as a photodiode 2330. In some versions one or more of the materials  
15 2350, 2360, 2370, may be conductive and the tip used in a tunneling mode for sensing, and/or the tip used to modify the memory element using any of the memory modification techniques which use such a tip. The use of the electromagnetic radiation may then be used as a  
20 sensor to read the media.

This version also has an additional advantage in the sensing of large particles, as in Figure 24. A large particle 2400 casts a complete shadow area in region 2410, and a penumbra in region 2420. The shape

of these will vary due to quantum effects of the  
emanated photons. As the media moves to the right  
relative to the head, the tip assembly 2430 senses a  
strong decrease in light, indicating the presence of an  
5 obstruction or particle in the path of the beam. The  
control system instructs the head assembly to lift, so  
that the obstruction passes under the head assembly,  
rather than striking it.

10 **MEMORY TECHNIQUES**

In the following descriptions, first the different  
techniques for reading and writing the memory surface  
will be discussed, followed by descriptions of  
apparatus for a molecular memory integrated circuit.

15

**Detailed Description charge storage read/write memory  
system**

The following description is for one tip/head.  
20 Typically, all platforms and tip/heads are operated  
simultaneously, with data being multiplexed by time  
division multiplexing to/from A/Ds and D/As through  
transmission gate muxes. Alternately, one row of  
platforms with all tips/heads may be operated  
25 simultaneously. Alternately, only one tip/head per  
platform may be operated simultaneously.

In addition, when power is first applied to the system, a calibration sequence is entered (see calibration).

Note: The X and Y actuators operate in pairs.

5 Normally, only one of the pairs receives an active control signal at any time. For example, to move to the extreme left, the left actuator receives a signal to move to the maximum position (typically 50u), and the right actuator is left off.

10

**Typical READ operation:**

1) A Digital Signal Processor takes data of where scan sector/track (X,Y coordinates) is to a start position, and loads parameters which initiate a ramp to  
15 the desired coordinates. Normally, this will be to a position near a "sector" mark on the X axis, with Y position being a desired "track". The media has a series of marks which consist of trenches or raised areas, typically 1u wide, which do not contain any  
20 data, but are used to identify the beginning of blocks of data. In addition, in systems which have moving media, control systems will move the media to a position, normally consisting of one of 9 positions, +/-center/- of X and Y.

2) Once the start position is reached, tip/heads begin oscillating at slightly off resonance and start moving towards media. The oscillations of the tip/heads, in one embodiment, are produced via a thermal heater supplied with current at resonance frequency. The thermal heater is embedded in a cantilever arm attached to the head tip and causes the tip to vibrate. For example, referring to Fig. 47, a cantilever arm in view A is shown constructed of an Oxide and Aluminum conductor (other conductor or insulative materials may also be utilized). A heating element 4751 is attached on top of the Oxide layer (other positions and attachments of the heating element are also suitable). The Aluminum is heated via an electrical current applied to the heating element at an approximate resonant frequency of the cantilever arm. The thermal expansion and contraction of the Aluminum conductor cause the cantilever and tip to vibrate at that resonant frequency.

Other materials may be substituted for the Al. In one embodiment, Ti is used, other substitutes include PolySi, NiCr or other hi-r materials.

A feedback loop of the tip/head will look for phase shifts in the signal coming back from the

piezoresistors sensor on the tip/head cantilever, indicating proximity to the media surface. In one embodiment, this feedback signal is generated by changes in the resistance of single crystal (or poly-silicon) doped silicon due to stresses in the film (for example, 4750 of fig. 47, which detects both phase changes of a vibrating cantilever/head, and position of the cantilever based on stresses placed on the piezoresistors).

3) As soon as all tip/heads on a platform have engaged the media, a scan can begin. A DSP optimized control signal, similar to a ramp (the DSP functions to produce a ramp voltage to move the actuators to a new position as opposed to applying the voltage all at once, thereby preventing overshoot of the actuator) is applied to the X actuators. The data returning from each of the tip/heads is manifested in a phase shift from the nominal (or near free space) drive frequency of the Z actuator. In addition, there will be a phase shift due to proximity of the tip to the media surface which is based on the gap at the shortest distance the tip travels towards the media. And in addition to that phase shift the magnitude of the phase shift due to the data will be based on the tip potential and the



charge potential of the domain under the tip. These two phase shifts will be used for various purposes. First, a phase shift due to the media surface is used to position the heads relative to the surface initially. The second phase shift is used to acquire data.

As shown in Fig. 47, in one embodiment, positioning of the heads via a cantilever is shown. In view A, the cantilever is in an uncurled position. An amount of current is sent through a heating layer (comprising a resistor, for example), heating the Ox and Al layers. The Aluminum layer has a higher coefficient of expansion than the Oxide layer, which is also relatively less affected by the heat generated via the current. The Aluminum and Oxide expand at different rates, causing a curl effect of the cantilever assembly, as seen in view B. A sensor layer embedded in the cantilever for detecting how far the cantilever has moved. In one embodiment, the sensor comprises a set of piezoresistors 4750, one piezoresistor being placed at a position in the cantilever such that it is bent during the curling of the cantilever more than a second piezoresistor. Each piezoresistor also has a resistance change due to

temperature change. The bridge formed by the two piezo resistors provides a means to cancel out the effect of the changing heating on the piezoresistors (both resistors are equally affected by the temperature change). However, since one of the piezoresistors will be affected more strongly by the change in film stresses due to curling, the result will be a net change in the potential across the bridge, but only due to the stress, not the temperature change.

10       At the beginning of the scan the cantilever is put in a mode to sense the media data. A guide mark (servo line) made out of a physical trench, typically 1u wide, which marks the beginning of a track. The interface will sense this as the phase from the piezo electric position sensor will shift towards the free space value. When it shifts back (the sensor is past the trench), the track read will begin (the cantilever changes modes from sensing the surface to sensing the data).

20       In one embodiment, there will be an initial set of charge domains which, encoded in some form of NRZ, which will encode the track (or Y) position. Once this is read and decoded it will be compared with the desired position. If it is incorrect, the difference

information will be used to reposition the platform for a retry. Once the correct track is in scan progress, data can be decoded from the stream of phase shift information.

5           A fine track position mechanism will be in effect to keep the platform positioned on tracks.

          In one embodiment, the tracks for data are optimally laid out such that sequentially positioned (in Y) track data is 90 degrees phase shifted from the  
10       previous track. This provides for tight packing of the data. In addition, the phase of the clock embedded in the NRZ encoded data will be flipped 180 degrees after every pair of tracks. This means that the track immediately adjacent to any track will have phases 180  
15       degrees apart. In the sampled data from the cantilevers, should the tip wander off track, data will begin to appear from the adjacent track. The phase of this data, relative to the current track, will indicate which side of the track the tip is wandering in, so  
20       that an opposing control signal can be supplied to move the tip back on track.

          A Z positioning mechanism will use the average phase shift and the desired average phase shift and move the tip/head up or down to maintain a constant

distance of the minimum tip gap point during oscillations while scanning across the surface. Although a resonant scheme is slower than dragging the tip in contact with the surface, the resonant scheme  
5 allows for a completely non-contact form of media interaction - thus minimizing tip wear.

A particular track is identified by reading a first few encoded data bits on each track that uniquely identify each track. Only enough bits are utilized to  
10 uniquely identify the correct track, alternatively additional bits may also identify a particular sector. In yet another alternative, a minimum number of bits may be used to identify a particular sector. In preparing to read data from the media, the cantilever  
15 swings the tip down to acquire the surface of the media (note tip position A, Fig. 44). After acquiring the surface, the tip moves in a direction towards data written on the media until it encounters a guidemark (servo line, or servo trench) which is detected because  
20 a free space value of the vibrating tip/cantilever is recognized. After recognition of the servo line, the height of the tip is adjusted to read the data. The free space value reference is a phase shift from the vibrations occurring while the tip had acquired the

surface of the media. After adjusting the height of the tip to read data, any new phase shifts that occur are due to data stored on the media after the servo line.

5 In one embodiment, a mechanism for determining whether or not the tip is drifting between tracks utilizes a set of sync bits that are set in a predetermined sync bit area set at predetermined intervals among each of the tracks. The sync bits are  
10 previously written as shown in the sync bit area of Fig. 43. The sync bits are utilized as described with the reference to Track 2. When encountering a first boundary of the sync bit area, the tip on Track 2 should be vibrating at approximately a free space value  
15 until the second bit on Track 2 in the sync bit area is encountered. The second bit in the synch bit area of Track 2 is a written (high) synch bit (represented as a darkened circle in sync bit area on Track 2), and when the tip passes over the written (high) synch bit,  
20 the tip will vibrate according to interaction with the written (high) sync bit. As the tip passes over the third sync bit on Track 2, the tip will have returned to its approximate free space value (approximate because of minor interactions with the media,

environment, etc.)). If upon entering the sync bit area on Track 2, the tip is not vibrating at the free space but instead is vibrating closer to what would indicate a written bit shows that the tip has drifted towards

5 Track 1 because it would be reading the first darkened circle representing a high bit on Track 1 in the sync bit area. If the tip were drifting towards Track 3, however, the tip and cantilever would still be vibrating at the free space value and only until the

10 tip reached a position for the second bit would the vibrations indicate being off of Track 2, in this case those indications being that it would be vibrating not at the free space value but slightly above the free space value because close proximity to the first

15 darkened circle (high bit) located in Track 3. Thus, more than one bit position in the sync bit area is utilized to determine drift.

The sync bits may also be utilized to assure that the tip is positioned a proper height above the media

20 surface. For example, again following along Track 2 and entering the sync bit area, if the tip is vibrating at other than the free space value, it would indicate that the tip is too close and is acquiring the media rather than acquiring bits written in the sync bit

area. Along the same lines, if at the second bit position within the sync bit area (and therefore over the first darkened circle, high bit, on Track 2 in the sync bit area) and tip were not vibrating at a frequency indicating a data bit having been written, but instead was vibrating at the free space value, this would indicate that the tip is too high above the media surface. Sync bit areas as illustrated in Fig. 43 may be provided at an interval that maintains the tip on track based on position accuracy of the hardware moving the tip. For example, precise hardware may only need one sync bit area within each sector, while less precise hardware may require additional sync bit areas within each sector. In one embodiment, sync bit areas are maintained every 32 bits to maintain the cantilever and tip on a specified track. Because the sync bits are phased at slightly different positions between tracks, the drifting between tracks may be detected as the tip passes specific positions in the sync bit area.

20

**WRITE operation:**

A write operation is essentially identical to a read except for the following difference:

In one embodiment, when the data portion of the track is reached, each time the tip swings down to its closest point to the media surface, a write pulse of appropriate polarity is applied to the tip. If a charge already exists, an opposite polarity pulse will remove the charge (making the data point a free space value, meaning when the tip passes over the data point, it will vibrate at the free space value). If no charge exists, an appropriate pulse will store the charge. In an alternate mode, the tip may remain in contact with the surface during writing.

**Calibration:**

After power up, the system will perform a calibration sequence. This involves:

1) Driving all the Z actuators in free space (well above the media) over a scan range (scan ranges of 70-130Khz and higher) to determine the resonant frequency of each tip/head/actuator system, and setting the drive frequency tables accordingly.

2) Moving all platforms to the extreme corner positions, initiating scans, and determining the coordinates of the extreme scan positions, as well as the center positions (in Y, for example), to set the



coefficients for ramping the Y position controls. This process is performed in both x and y position controls. The control system will first perform a scan from left to right, and time the scan from grid mark to grid mark  
5 across the extremes of positions. This can be performed at slower than normal speed for increased accuracy. This timing information can be used to adjust the X speed controls, as well as the X position controls. The scans can be performed at different Y  
10 positions, and likewise in the Y axis. This will calibrate the X and Y positioning and speed controls.

Thus, by driving the heads and determining timing between servo marks, it can be mathematically calculated how much force (current/voltage) is needed  
15 to drive the actuators to place the media and platforms in specific positions. Such information is maintained in tables or other data storage. The DSP utilizes the stored data with respect to driving the x-y actuators and resonant frequencies to determine a ramp to send to  
20 the actuators to position the media and platforms.

Each cantilever is tested by the DSP by applying a current at different frequencies to each cantilever to determine resonant frequencies (via amplitude peaks) of each cantilever. The resonant frequencies will be

maintained by hardware or software in a table, and utilized in tip operations (reading, for example).

**Formatting:**

5           Like any non-volatile memory, the system needs to be formatted. To aid the process of formatting, a set of guide (servo) marks will be etched in the surface of the media. In one embodiment, these marks will consist primarily of 1u lines, in a grid pattern. Then a  
10       series of write tracks will be executed, which write all the tracks with known data and track position information.

**Detailed Description magnetic read/write memory system**

15           The magnetic system is similar in most respects to the charge storage system, with the following differences:

**Typical READ operation:**

20           Same as 1, 2, and 3 above (typical read of charge storage system), except that the phase shift is due to interaction of magnetic material on a coated tip of the cantilever and magnetic domain under the tip and in the media (medium).

**WRITE operation:**

A write operation is essentially identical to a read except for the following difference:

When the data portion of the track is reached,  
5 each time the tip swings down to its closest point to  
the media surface, a write pulse of appropriate  
polarity is applied to the write/sense coil. This  
creates a magnetic field which induces a field in the  
ferrous coated tip (Co, for example), which then flips  
10 the polarity of the domain immediately under the tip.  
The duration of this pulse must be short enough to  
prevent driving the tip into the media, yet long enough  
to flip the domain (which fortunately can be achieved  
in a short time span). The intensity must be  
15 controlled for the same reason. For example, Fig. 37  
shows a bias coil 3700 that emits a bias field over the  
whole molecular memory device (read/write portion of  
the device). An individual write sense coil 3710 in  
close proximity to a corresponding tip 3720 applies a  
20 field to write the media. The tip 3720 collects and  
concentrates the bias and write fields at the point  
where the write is to occur.

**Alternate write operation technique - synchronous write**

When the data portion of the track is reached, all of the tips or a block of tips are moved towards the media and positioned at the closest point ONLY if a bit  
5 of a certain state is to be written for that bit. If an opposite state is destined for a bit, the tip is moved away from the media. When all the tips of the appropriate state are at their closest point to the media surface, a write pulse of appropriate polarity is  
10 applied with an external coil. This creates a magnetic field which induces a field in the Co coated tip, which then flips the polarity of the domain immediately under the tip. A second pass is then initiated to write all the bits of the opposite state. The Z head/tip  
15 assemblies may be periodically switched back to a resonant sensing mode to ensure that the assemblies are still tracking the desired tracks correctly (in one embodiment, by reading sync bits).

This technique has the advantage of overcoming the  
20 small fields producible by the individual write coils by substituting a large field coil. It has the disadvantage of requiring a slower write time.

**Memory techniques using current flow and fine tip**

In the previously described techniques, the tip/media interaction operated in the tunneling regime, a distance nominally from 1 to 10 Angstroms between the tip and the media. A larger distance is typically referred to as the field-emission regime. Nominally lower currents flow in this regime and the current is also largely affected by the presence or absence of environmental gases. A smaller distance we will refer to as the purely resistive regime. In this regime, one or more atoms of the tip will be within a range which will allow substantial currents to flow between the tip and the media.

In the field-emissive regime, provided sensitive enough electronics, the sense mechanisms will still operate all the described memory techniques. Provided also that the voltage is raised to a high enough value, the memory element altering mechanisms will also operate for all those techniques which require an electrostatic force to operate.

In the purely resistive regime, the sense electronics need be much less sensitive, providing for much simpler sense electronics. An important consideration in the resistive regime is that the tip

generally not move laterally over the media surface while sensing or altering the media in order to reduce tip wear. Here again, the same mechanisms will operate for all those techniques which require an electrostatic  
5 force to operate.

In addition to the Memory techniques already described in the previous patent (Rust, et al., U.S. Patent 5,453,970) are the following techniques:

10 **Memory Technique 1**

For this technique, an example surface and memory element is doped diamond. The memory altering technique is the same as Technique 6 in the previous application.

15 In this technique depicted in Figure 19 any one of the disk drive apparatus in the previous patent application or the MARE IC is used and a molecular memory comprising atoms or molecules and a memory element comprising atoms or molecules exists on the  
20 same plane as the surface of the rotating disk or a fixed or moving plane above the MARE IC.

When a pulse of greater than 23V is applied of typically 100ns, the new lattice state of the diamond

is in the form of a donut shape 2000 typically 30nm wide by 10 nm high as shown in Figure 20.

## Memory Technique 2

5           For this technique, an example surface is silicon, the memory element are electrons or depleted electrons (holes) stored on a thin insulator such as silicon dioxide.

10           In this technique depicted in Figures 26A-D, the memory element comprising electrons or holes exists as a thin layer on the surface of a rotating disk or fixed or moving surface.

          The unwritten state is depicted in Figure 26A.

15           To effect a written state in the memory, a head tip 2600 is positioned above or at the plane of the insulator 2610. When it is desired to write a bit of data, a bias voltage is applied between a tip and a memory element 2620. The bias voltage stores a charge in the form of electrons or holes 2630 as the memory  
20   element. It is possible to store analog information by using a larger or smaller bias voltage as well.

          To read the information stored, the tip is passed over the surface in the same manner as writing. The electronics are put in a read mode. The read

electronics discharges the electrons or holes to sense the information. The information is then restored in a subsequent re-write.

A disadvantage of this technique is that it  
5 requires re-writing the information after every read.

### Memory Technique 3

For this technique shown in Figure 25, an example  
substrate surface is silicon (S) 2540, the memory  
10 element are electrons or depleted electrons (holes)  
2530 stored on a thin material such as silicon nitride  
(N) 2510. Below the top layer material is a tunneling  
insulator such as silicon dioxide (O) 2550. A  
tunneling insulator is a thin layer of material which  
15 is conductive if a threshold bias is exceeded. This is  
referred to as a NOS structure.

In addition, one of several techniques are used to  
improve the performance of this structure. In one  
form, a series of trenches are fabricated in the  
20 substrate 2540 and the NO or ONO structure is formed  
over the surface of the trenches. This has the effect  
of increasing the effective capacitance of the  
structure by a large factor causing a larger change in  
capacitance (stored charge) between a written and non



written area of the media. In addition, the preformed structure of trenches serve as guides for the tracking servo mechanism.

In another form, a processing technique is used to  
5 etch the NO areas N 2510 and O 2550 into discrete islands. In another technique, in addition to forming the islands, additional doping is injected into the regions between the islands. Both of these techniques have the effect of allowing smaller bits to be formed.  
10 In the additional doping technique, the bits tend to have deeper depletion regions as well.

The unwritten state is depicted in Figure 25A.

To effect a written state in the memory, a head tip 2500 is positioned above or at the plane of the  
15 insulator 2510 at 2520. When it is desired to write a bit of data, a bias voltage exceeding a certain threshold is applied between a tip 2500 and a substrate 2540, creating memory element 2530. The electrons tunnels to/from the substrate material and stores a  
20 charge in the form of electrons or holes as the memory element on the insulator 2510. It is possible to store analog information by using a larger or smaller bias voltage as well.

In one embodiment, to read the information stored, the tip is operated on a cantilever operating in a resonant mode. As the tip passes over a region of stored charge, based on the potential of the tip and the potential of the charge, a force will be exerted between the tip and the stored charge which will alter the phase of the cantilever.

In an alternate embodiment, the tip is passed over the surface in the same manner as writing. The electronics are put in a read mode. The existence of a charge forms a depletion layer in the substrate 2540, effectively changing the relative capacitance of the region between the substrate and the surface. A read technique which senses the difference in capacitance of written and unwritten states may be used.

#### **Memory Technique 4**

This technique is shown in Figures 18 and 19. For this technique, an example substrate surface is silicon (S) 1870 and 1970, the memory element are electrons or depleted electrons (holes) 1830 and 1930 stored on a thin material such as silicon nitride (N) 1810 and 1910. Below the top layer material is a tunneling

insulator such as silicon dioxide (O) 1840 and 1940.  
A tunneling insulator is a thin layer of material which  
is conductive if a threshold bias is exceeded. This is  
referred to as a NOS structure. In addition, in the  
5 top layer of the substrate, an oppositely doped region  
(from the bulk substrate) is formed. Electrodes 1805  
and 1815 are placed to form contacts to this doped  
region in two places opposite the region where charge  
is to be stored. The result is to form an active gate  
10 region under the NO.

The unwritten state is depicted in Figure 19A.

To effect a written state in the memory, a head  
tip 1800/1900 is positioned above or at the plane of  
the insulator 1820/1920. When it is desired to write  
15 a bit of data, a bias voltage exceeding a certain  
threshold is applied between a tip 1800/1900 and the  
substrate 1870/1970, creating a memory element under  
1820/1920. The electrons tunnel to/from the substrate  
material 1970 and stores a charge in the form of  
20 electrons or holes as the memory element on the  
insulator 1910. It is possible to store analog  
information by using a larger or smaller bias voltage  
as well.

To read the information stored, the tip is passed over the surface in the same manner as writing. The tip is set to a bias voltage for the read mode. A potential is applied between the two electrodes. The  
5 existence of a stored charge 1830/1930 forms a depletion layer in the doped region. The existence of the read mode bias adds to the induced field, raising the field enough to create an inversion region in the doped area 1860/1960. The existence of the inversion  
10 region will cause a current to flow between the electrodes 1805 and 1815, greater than that which would occur without the tip-induced field.

This greatly simplifies the electronics needed for this type of memory device.

15 In an alternate embodiment of this technique, the doped regions are formed into narrow channels between sets of two electrodes. The existence of the sets of narrow channels allows the ability to select which regions are to be read or written by selecting the  
20 electrodes.

In one embodiment, the molecular memory media (storage medium) is produced by depositing layers similar to those seen in the previous figures (figures 18 and 19, for example) with the substrate

being modified such that it has many wells (or pits) at locations where bits are to be stored in the media. For example, referring to Fig. 46, a substrate having wells (or pits) 4600 at predetermined intervals is shown. The substrate is then coated with a doped area and a variety of insulators similar to those shown in the previous figures (layers 4610). The wells provide a structure having increased capacitance for charges stored at each hole, therefore providing increased charge retention and easier detection of data bits written. In one embodiment, the wells (or pits) are patterned (or otherwise formed) into the substrate at a surface of the substrate prior to applying the additional layers 4610. In another embodiment, the wells take the form of a honeycomb shape produced from the substrate material. Layers 4610 are then deposited over the honeycomb shape.

#### Memory Technique 5

In an alternate media embodiment, the media consists of structures forming quantum dots. These may be formed using multiple quantum well (MQW) techniques. The media is written by applying a voltage pulse

sufficient to change the electron state energy in the trapped quantum well regions.

#### Memory Technique 6

5           In this technique, the memory substrate consists of a material such as silicon (Si). The substrate has the property of two or more bonding interface states with the layer of atoms or molecules (memory elements) in the adjoining layer.

10           This technique is similar to Memory Technique 6 in the previous application, but with several differences in the way the memory elements are read and written.

          To effect a written state in the memory, a head tip 1900 is positioned above or at the plane of the  
15   memory element layer. When it is desired to write a bit of data, the tip is moved laterally with respect to the memory element layer at a rate  $V_T$  for tip velocity. At the same time, a periodically fluctuating bias voltage (VBF) of a sufficient amplitude to move the  
20   memory elements is applied. The fluctuating bias matches the energy level of the selected media material. The distance between bond center of a substrate-memory element bond, in one of the desired states is DBCS1 (distance bond centers state 1).

VBF will be of such a frequency to be a harmonic relationship of TV/DBCS1. (Alternatively, the TV may match the VBF vs. the lattice structure of the media.) A phase relationship which correctly applies the forces  
5 relative to the bond centers may be applied, such that the memory elements are lifted and then forced to fall into the least bonding barrier energy well associated with that state, and so form a structure with that state. This forms a bit in one state B0 (bit value 0).

10 A VBF with a different frequency and phase is applied to form a bit in another state, where VBF will be of such a frequency to be a harmonic relationship of TV/DBCS2, where DBCS2 (distance bond centers state 2) is another stable state bit value 1 (B1). If there are  
15 more than 2 stable states, the memory element may hold more than 1 digital bit.

To read the memory, the tip is passed over the surface using any of several forms of reading where either current or topological information is read back  
20 to indicate the positions of the memory elements. The signal indicating data B is applied to any form of filter which distinguishes between the characteristic frequencies of each of the states of the memory elements. For example, in a two state system, a low

pass filter with cutoff frequency between the characteristic frequencies of the two states, followed by an integrator and comparator would output one voltage (bit) for one state and another voltage for another state. The use of two bandpass filters, each with their own integrator and comparators, would indicate valid data states and invalid data states.

#### Memory Technique 7

For this technique, referring to Figs. 48 and 49, an example substrate surface is silicon (S) 4870, the memory element are a combination of electrons and depleted electrons (holes) stored on a thin material insulator such as silicon dioxide (O) 4840 and a top layer of the substrate (an oppositely doped region 4860). Either the thin material insulator or the oppositely doped region may store the elections and the other storing the holes, or vice versa depending on the polarity of the tip relative to the substrate. Electrodes 4805 and 4815 are placed to form contacts to this doped region in two places opposite the region where charge is to be stored. The result is to form an active gate region under the oxide.

The unwritten state is depicted in Figure 49A.



To effect a written state in the memory, a head tip 4800 is positioned above or at the plane of the insulator 4820. When it is desired to write a bit of data, a bias voltage exceeding a certain threshold is applied between a tip 4800 and a memory element 4820. The electrons tunnel to/from the substrate material 4870 and stores a charge in the form of electrons or holes as the memory element on the insulator 4840 and oppositely doped region 4860 at 4830. It is possible to store analog information by using a larger or smaller bias voltage as well.

To read the information stored, the tip is passed over the surface in the same manner as writing. The tip is set to a bias voltage for the read mode. A potential is applied between the two electrodes. The existence of a stored charge at 4830 forms a depletion layer in the doped region 4860. The existence of the read mode bias adds to the induced field, raising the field enough to create an inversion region in the doped area 4860. The existence of the inversion region will cause a current to flow between the electrodes 4805 and 4815, greater than that which would occur without the tip-induced field. This greatly simplifies the electronics needed for this type of memory device.

In an alternate embodiment of this technique, the doped regions are formed into narrow channels between sets of two electrodes. The existence of the sets of narrow channels allows the ability to select which regions are to be read or written by selecting the electrodes. This technique has the advantage over technique 5 in that the erase times are typically much faster, and programming voltages can be much lower because a single material that is very thin and a potential needed to perform tunneling can be therefore done with a lower voltage.

#### **Memory Technique 8**

The memory media consists of a ferromagnetic thin film layer. The tip of the Z cantilever consists of a tip region of a ferromagnetic material which may be surrounded by a hard buffer material which is not ferromagnetic, typically a hard insulator such as silicon nitride. The apparatus is placed in a pulsed magnetic field.

To write a bit, the tip is brought into proximity to the media, then the magnetic field is pulsed. To read a bit, the tip is brought into proximity of the media while vibrating at a resonance frequency. The

force of the magnetic attraction or repulsion caused by a written bit will change the resonant frequency and the phase of the oscillation will be shifted.

5    **Drive Apparatus 1**

Figure 30 shows one embodiment of one cell of an array of a molecular array read/write engine (MARE) memory integrated circuit apparatus according to the present invention. Not shown is the media itself,  
10    which is placed over the MARE device. External electronics interface through I/O pads (not shown). These pads pass both analog and digital information to/from the MARE. This information contains data to be written and data read from the memory, positioning  
15    information for the actuators, and position feedback information from the actuators. The cell contains pairs of X actuators 3200 and 3210, Y actuators 3220 and 3230, connecting leads 3240, 3250, 3260, 3270, and the platform 3300 consisting of 12 sets of assemblies  
20    consisting of Z actuators with cantilevers, heads with fine tips, position sensors, read/write coils 3400, 3410, 3420, 3430, 3440, 3450, 3460, 3470, 3480, 3490, 3500, 3510, and nub assemblies 3600, 3610, 3620, 3630, 3640, 3650, 3660, 3670. Patterns with an X shape

(3671, for example) are holes in the platform to allow etchants to flow under the platform and release the platform more quickly.

5 The Z actuators with cantilevers, heads with fine tips, position sensors, and read/write coils are shown in detail in Figures 31, 32, and 33. The spring and actuator assemblies are a multi-layer film of highly conductive patterned thin film (typically aluminum, other materials will suffice (copper, for example) with  
10 insulators in between the layers (typically silicon dioxide). Z motion (in and out of the plane of the surface of the platform) is effected by electrostatic force. There are two sets of moving fingers 4000 and 4010 interdigitated between two sets of non-moving  
15 fingers 4020 and 4030. The moving fingers are mechanically tied together, tied to cantilever 4090 and mechanically coupled to a pair of electrically isolated torsion bars 4040 and 4050. Conductor plate 4055 which crosses the torsion bars and is electrically isolated  
20 from the tip torsion bar 4040 is electrically connected to the Z drive conductor which is also torsion bar 4050. The torsion bars are mechanically clamped at points 4060 and 4070. Cantilever 4090 is connected electrically to torsion bar 4040 and tip region 4100.

The moving assembly consisting of fingers 4000 and 4010, torsion bars 4040 and 4050, conductor plate 4055, cantilever 4090 and tip 4100 form a teeter-totter assembly which rotates between the points 4060, 4070  
5 twisting the torsion bars 4040 and 4050.

A cross section of the fingers assembly is in Figure 13. The conductive part of the moving fingers are conductors 1300 on top of insulator 1320. The fixed conductors are 1310. An electrostatic potential  
10 is applied between conductors 1300 and 1310. The attractive force pulls the fingers 1330 in Figure 13, 4010 in Figure 32, downward. An opposite arrangement is configured on the other side of the fulcrum. The raised conductors are the fixed conductor fingers,  
15 while the lower conductors are the moving conductors. This produces the effect of forming a rising force on the fingers 4000. The net effect is two forces, one downward on the 4010 side of the torsion bars, the other an upward force on the 4000 side of the fulcrum  
20 formed by the torsion bars. This motion is typically a fraction of a micron. This movement is amplified by cantilever 4090 to form a motion of the tip 4100 of typically a 5-10 microns.

The tip region 4100 (see Figure 31 and magnified in Figure 33) is surrounded by a coil 4110. The tip region is coated with a magnetic material such as Co (cobalt), additional thicknesses of magnetic material may be added in the region adjoining the tip 4120. The motion of the tip region in and out of the plane of the coil induces a current in the coil, which can be used to sense the position of the tip, the proximity of the tip to a surface and the intensity and direction of the magnetic domain beneath the tip. Additionally, a current applied externally to the coil creates a magnetic field which induces a concentrated field at the tip region. An external biasing magnetic field may also be applied to augment the small field of the coil.

15 The concentrated field, when in the proximity of a domain of the media, causes the direction of the field of the domain to align with the direction of the write field, overcoming the point coercivity of the media.

Referring again to the actuator of Fig. 32, it has several advantages over other embodiments. It can be fabricated from as few as two materials, a conductor typically aluminum or poly-silicon and an insulator, typically silicon oxide. The process is self-aligning, in that the top metal layers form a mask. A subsequent

anisotropic oxide etch clears any unwanted bridges between moving parts. Normally this actuator is formed over a silicon substrate.

Another significant advantage of this actuator  
5 over the actuator in Figure 10 is that travel of the  
fingers up and down in the Z plane is not limited by  
contact of the upper plate 1500 with the lower plate  
1510 as in Figure 10. Another advantage is that there  
is not contact between the upper and lower conductors,  
10 which in the case of Figure 10 would short the plates,  
removing the attractive potential, and potentially  
damaging the plates and associated electronics.

A typical problem with micromechanical devices is  
stiction. Once components touch, they tend to need a  
15 disproportionally large force to separate them. Since,  
in the embodiment of Fig. 32, the fingers do not touch,  
even at the travel extremes, stiction is not a problem.

The X and Y actuators are shown in more detail in  
top view Figure 34A and cross section Figure 34B. Each  
20 arm 4200 consists of 3 prongs 4210, 4220, 4230. The end  
prongs 4210, 4230 are each made of a stack of optional  
bottom dielectric OX1 4300 (see Fig. 34B), conductor M1  
4310, dielectric OX2 4320, conductor M2 4330 and  
optional top dielectric OX3 4340. Additional

dielectrics may be added to increase stiffness in the Z plane which helps reduce bowing of the actuator due to film stresses.

The polarity of the conductors is reversed in the center prong 4220 for M1 and M2. When a voltage potential is applied to the two conductors, an electrostatic force is created which attracts the end prongs to the center prong. As actuation increases, the gap (between prongs) is shortened (4201 and 4202, for example). All of the prongs acting together generate a force which tends to make the actuator compress and reduce all the gaps. Additionally, the arms aligned at an angle to each other and the actuation axis allows for lower spring constant in the opposite axis.

Of each of the pairs of X actuators 3200 and 3210 and Y actuators 3220 and 3230 (Fig. 30, for example), one of the pairs is normally not actuated when the other is being actuated. For example 3200 pulls the platform to the left, 3210 to the right, 3220 pulls up, 3230 pulls down. However, additionally, the normally off actuator of the pair may be actuated to act as a brake, thus improving deceleration performance.



Each platform also contains a set of 8 nub assemblies 3600, 3610, 3620, 3630, 3640, 3650, 3660, and 3670. The nubs are a platform consisting of an array of one or more sharp tips, typically of the same configuration as the tips on the cantilevers. When the media surface is placed over the MARE, if the platform has any bow which causes it to bow towards the media surface, the tips of the nubs will touch the media surface, and thus keep the platform at a fixed distance relative to the media. The very low surface area of the tips reduces the friction between the platform and the media.

A separate media contactor assembly 3100, similar to the above Z actuators with cantilever and head with fine tip, provide a means for electronically controlling a physical and electronic contact with the media. When input pads are given a control voltage of high enough value, the tip is raised into position against the media and electrical connection to the media via a separate input pad is achieved. When no voltage is applied to pads, the Z actuator remains in the off position and the media is electrically isolated from the media biasing voltages as a safety means. This applies only to media which require an electrical

connection. More than one contactor may be implemented as backup or to provide more uniform current flow over the media. Alternately, connection to the media may be effected by bonding to the back side of the media  
5 wafer.

Each of these cells described above may be integrated into arrays of cells to increase the capacity of the drive. In the simplest form, diodes are placed around each cell to allow each cell to be  
10 individually addressed, or addressed by rows and columns selectors. In alternate forms, interface electronics are embedded near each cell.

#### **Alternate Drive Apparatus 2**

15 Figure 35 shows an embodiment of a MARE device with an array of platforms utilizing a modified electrostatic comb drive for X and Y actuators. This apparatus is identical to the Drive Apparatus 1 with the difference being the type of X,Y actuator. Figures  
20 35B and 35C show this actuator in detail. The actuator consists of a fixed comb 4600, a moving comb 4610, comb-to-flex rod coupler 4625, coupling flex rod 4620, coupling bars 4630 and 4640, thin flex rods 4650, 4655,

4660, 4665, 4670, 4675, 4680, 4685, and fixed holders  
4690 and 4700.

When a voltage is applied between the inputs 4710  
and 4720, the voltage is carried by conductors through  
5 the thin flex rods and coupling bars to the moving  
comb, so the voltage appears between the two combs. In  
Figure 35C a detail of the fingers of the combs are  
shown. These fingers employ a different architecture  
from normal comb drives. By employing notches on each  
10 finger, the surface area of the combs is increased  
(nearly a factor of 2 increase occurs in the embodiment  
of Fig. 35C, other increase factors may be realized via  
varying geometrics and dimensions), thus increasing the  
electrostatic force by an amount comparable to the  
15 increased surface area

The notches are staggered in their position to  
reduce the non-linear effect produced by the difference  
in gap distance from a notch facing a notch and a notch  
facing a bar. The electrostatic force pulls the combs  
20 together. The force is coupled by the thin flex rods  
to coupling bars 4630 and 4640, which move at about  $\frac{1}{2}$   
the speed of the moving comb. This structure has a  
large rigidity in the Y axis, thus preventing the comb  
fingers from moving in the Y axis and touching. In

addition, a spring action of the thin flex rods and the coupling bars brings the combs and coupling flex rod back to their original positions. The actuation movement is coupled through 4625 to coupling flex rod 5 4620, the end of which is attached to the platform. This flex rod is designed to be able to bend in the Y axis, when the platform is moved in Y.

Any of the notching techniques described herein may be utilized by any of the electrostatic devices and 10 drivers also described herein.

### **Alternate Drive Apparatus 3**

Figure 36 shows an embodiment of a MARE device with an array of platforms utilizing a thermal drive 15 with capacitance sensor for X and Y actuators. This apparatus is similar to the Drive Apparatus 1, one difference being the type of X,Y actuator. Figures 36B and 36C show this actuator in detail. The actuator consists of four sets of thermal actuators 20 5000,5010,5020,5030, a fixed comb portion of the capacitance sensor 5040, and a moving comb portion of the capacitance sensor 5050, connecting block 5060, flexible coupling rod 5070, and fixed blocks 5080 and 5090.

A cross section of one embodiment of the thermal actuator is shown in Figure 36C. It consists of an optional dielectric 5200,5205, metal 1 5210,5215, delectric 5220,5225, optional metal 2 5230,5235, and  
5 optional delectric 5240,5245. The combined thermal properties of block 5260 are such that it will remain cooler than block 5270, so block 5270 will expand more than 5260. The result is that the combined group will push towards the left in Figure 36B. The 4 actuators  
10 can be operated electrically in parallel or in series. Their combined force will sum, to push the moving comb sensor 5050, connecting block 5060, and coupling rod 5070 towards the left. The platform attached at the end of rod 5070 (not shown) will be pulled to the left.  
15 As the moving comb 5050 reduces the gap inside comb 5040, the capacitance of the assembly will increase. This capacitance can be used to sense the position of the actuator.

#### 20 **Alternate Drive Apparatus 4**

Figure 1 shows one embodiment of a molecular array read/write engine (MARE) memory integrated circuit apparatus according to the present invention. External electronics interface through I/O pads 10. These pads

pass both analog and digital information to/from the MARE. This information contains data to be written and read from the memory, positioning information for the actuators, and control information for the state engines. Input pad 20, input enable, when logic 0 enables the transfer of information from the pads to the platform assemblies 40 through the tri-state bidirectional buffer amplifiers 50. Input pad 30, output enable, when logic 0 enables the transfer of information from the platform assemblies 40 to the I/O pads 10 through the tri-state bidirectional buffer amplifiers 50.

Input pad 60 clock-reset, transfers a 3 state clock and reset signal, buffered by assembly 70 to each of the platform assemblies 40. Separate control signals for the X-Y actuators may optionally be supplied through input pads (not shown in Fig. 1). Power is applied via pads 80 for +, 90 for -. A separate pair of media contactor assemblies 100 similar to the Z actuators provide a means for electronically controlling a physical and electronic contact with the media. Input pads 110 and 120 provide both control voltages to raise the contactors into position against the media and electrical connection to the media via

pad 120. When no power is applied to these pads, the media is electrically isolated from the media biasing voltages as a safety means.

5 The data, control, and power information is conveyed to platform assemblies 40 shown in detail in Figure 2. The spring and actuator assemblies are a multi-layer film of highly conductive patterned thin film (typically aluminum) with insulators in between the layers (typically silicon dioxide). There are  
10 typically at least 2 conductive layers, one layer providing power (+ or -) or clock-reset, the other control and data. When a potential differential exists between any two layers of the film, an electrostatic force will be exerted in a direction relative to the  
15 generated electrostatic force lines. This force causes the spring actuators to either expand or contract. This expansion or contraction is used to move the central platform 210 which is suspended between the 4 spring actuator assemblies. Each spring actuator also  
20 embodies a compliance in a direction at right angles to the expansion/- contraction actuation, allowing the central platform to move freely in both X and Y axis. The motion generated by the actuators is typically controllable from -50 to +50 microns travel.

In another embodiment, a third layer embodies the layer used for carrying the X-Y electrostatic control voltages. The third layer has the advantage of electrical isolation from the other electronics.

5 Typical CMOS devices operate up to 15V. Breakdown voltage of thermal oxide is typically 600V/micron. The third layer metal typically has 1 micron oxide spacing. Therefore a control voltage up to 300V (thus with adequate safety margin) can be applied to this separate

10 layer. As electrostatic force increases by the square of the voltage, higher voltages are a distinct advantage.

In another embodiment, the actuators are thermal bimorphs consisting of a heater (typically poly-silicon resistor), and two materials of different expansion

15 coefficients, patterned with one material on one side and the second on the other side (see Figure 12 and cross-section Figure 15), such that applying current to the heater raises the temperature of the bimorph,

20 causing the bimorph to expand or contract. The heater is typically formed with polysilicon. Conductors and the material of higher expansion coefficient 1520 and 1530 are typically aluminum. The assembly is typically encased in oxide 1510. Heating will cause end 1250,



Fig. 12, to move to the left. Thermal bimorphs have the advantage of operation at lower voltages. They have the disadvantage of higher power dissipation, slower response (due to heat conduction and convection), and greater drift.

In another embodiment, the spring/actuators are electromagnetically controlled.

In another embodiment, the spring/actuators are controlled by shape memory alloy devices.

All of the embodiments may also use three actuator/spring assemblies instead of four, arranged at typically 120 degrees in a circle around the platform.

On the platform assemblies are control and state engine electronics 220 and one or more Z actuator tip assemblies 230 (in this case 8 assemblies). The Z actuator/tip assemblies are shown in Figure 4. These assemblies consist of electrostatic actuator 300, electrically isolated tip assembly 310, bridge or bridges 320. The actuator 300 consists of bottom electrodes 330, typically fabricated in the doped well or polysilicon (in double poly processes) and top electrode 340, typically fabricated in poly-silicon.

After post processing, which removes the oxide between electrodes 340 and 330 and under tip assembly

310, the top electrodes, tip, and bridge float above the bottom substrate, anchored at point 350. The bridge 320, typically formed with passivation glass, binds the actuators to the tip assembly. When a  
5 potential is applied to the electrodes 330 and 340, electrostatic repulsion pushes the top electrode upwards. The tip assembly is levered upward as well via the bridge.

By extending the tip beyond the edge of the  
10 actuators, the tip is leveraged a multiplying height factor approximately based on the number of times the extension is longer than the actuator. As the electrostatic force decreases by the inverse square of the gap, this leverage force is needed to provide a  
15 significant motion of the tip.

In an alternate embodiment, the electrostatic actuator and/or tip assembly is folded to conserve space.

In another embodiment, the Z actuators are formed  
20 with thermal bimorphs.

In another embodiment, the Z actuators are electromagnetically controlled.

In another embodiment, the Z actuators are controlled by shape memory alloy devices.

The tip region, after fabrication, may have an edge with sufficiently small radius of curvature to be useful as the read/write and sense region for interaction with the media. As a further refinement, a focused ion beam (FIB) deposition machine may be used to deposit a controlled fine tip material, typically tungsten or platinum, to provide a tip region with radius of curvature in the 10 nanometer range.

The FIB machine may also be used to mill down the deposited material in such a way as to form the tip region. Additionally, these machines may be used to subsequently analyze the resulting tip and ensure proper tip fabrication. Alternately, tips may be refined by sputtering of a tip material through an aperture to form a fine tip region. Alternately, the tips may be refined by etching through an aperture above the tip region.

In an alternate Z actuator/tip assembly, an additional piezo resistor, typically made from <100> oriented silicon is inserted in the actuator. This resistor will change resistance depending on the stress induced by the bending of the actuator (see Fig. 47, for example). This is typically amplified and read

back during operation. This information can be used to sense height of the actuator.

In an alternate embodiment, the tip can be operated in an AFM mode. In this mode, the tip is set  
5 into a resonant vibration mode above the surface of the media. The resonant mode is indicated by a maximum amplitude of travel with a minimum oscillating control voltage amplitude. When a tip approaches the surface, a slight phase shift will occur from a read-back  
10 oscillating height sensor amplifier 5010 connected to the tip.

An alternate Z actuator/tip assembly is shown in Figure 10. This device may include an optional capacitive position sensor for the Z axis (not shown  
15 but would be similar to that shown in Figure 9). Z motion (in and out of the page from the figure) is effected by electrostatic force. There is moving grid 1500 above fixed plate 1510. The moving grid is mechanically tied together and coupled to floating  
20 torsion bar comprising separate electrically isolated torsion bars 1520 and 1530 and bridge 1540 which crosses the torsion bars and is electrically isolated from the tip torsion bar.

The torsion bars are mechanically clamped at points 1550 and 1560. Finally lever 1570 is connected electrically to torsion bar 1530 and tip region 1580. The moving assembly consisting of grid 1500, torsion bars 1520 and 1530, bridge 1540, lever 1570 and tip 1580 form a teeter-totter assembly which rotates about the Y axis formed by the torsion bars 1520 and 1530. An electrostatic potential is applied between conductors 1500 and 1510. The attractive force pulls the grid 1500 downward. An opposite arrangement may be configured on the other side of the fulcrum (not shown) to provide a rising force on the left side of the fulcrum. The net effect is one or two forces, one downward on the right side of Figure 10, the other an optional upward force on the left side of the fulcrum formed by the torsion bars. This motion is typically a fraction of a micron. This movement is amplified by lever 1570 to form a motion of the tip 1580 to typically a few microns.

20 This actuator has the advantage of higher force per area due to the closer proximity and better alignment of the Z force along the Z axis over the actuator of Figure 9.

### Alternate Drive Apparatus 5

Figures 38 and 39 show an embodiment of a memory device with an array of platforms utilizing a thermal drive for X, Y and Z actuators and a separate, movable media. Figure 38 shows the platform with the Z actuators, Z position sensors, cantilevers and tips. Figure 39 shows the media platform which moves in a similar fashion as figure 38. Figure 39 is placed over figure 38 in normal operation. This apparatus is similar to the Drive Apparatus 1 with the difference being the type of X, Y, and Z actuators. Figure 38 may be used with either a fixed media or moving media such as figure 39. The X and Y actuators are similar to the drive in figure 36B and 36C without the capacitive position sensor. In addition, these actuators are placed in 2 stages, each consisting of 4 actuators operating in parallel, such that the position of stage 1 adds to the position of stage 2, thus doubling the travel of this actuator.

Figure 38 consists of X actuators 3800, 3810 and Y actuators 3805, 3815. The moving platform in the center area consists of Z assemblies 3820, 3822, 3824, 3826, 3828, 3830, 3832, 3834, 3836, 3838. These are shown in detail in figure 40. The Z assemblies are electrically

connected through insulated wires originating in fixed positions 3850,3852,3854,3856 and connecting to the moving platform. These wires also pass under and are physically connected to sets of tips anchored at  
5 locations 3840,3842,3844,3846. These tips act as bearings against a corresponding plate with optional grooves 3950,3952,3954,3956. These maintain a fixed space between the platform of figure 38 and the media of figure 39. The grooves in the plates may be used as  
10 a means to force scanning of the platform from figure 38 with the media in figure 39 to remain on a given track, thus making electronic servoing of track position simplified.

The media platform in figure 39 has similar X and  
15 Y actuators as figure 38, however, these need not be operated in a linear fashion. They may be operated in a simple on-off state to yield one of 3 positions for each axis, left, center, and right for the X axis, up, center, and down for the Y axis. These provide an  
20 offset of the media relative to the MARE device of Figure 38. The media blocks 3920, 3922, 3924, 3926, 3928, 3930, 3932, 3934, 3936, 3938 may contain regularly spaced marks to aid in positioning of the tips on the media. The media may have its substrate

electrically connected through a set of insulated wires anchored to fixed positions 3940,3942,3944,3946.

The Z actuator assemblies shown in figure 40 consist of cantilever block 4000 anchored to base at 5 4035, sharp tip 4005, electrical connection to tip 4025, heater element 4020, high coefficient of thermal expansion element 4030, piezoresistive sensor 4010 and piezo-resistance thermal compensation sensor 4015. The Z assembly is moved by applying a current through the 10 heater element 4020, which heats thermal expansion element 4030. Not shown is layers of insulating material, typically silicon oxide, which have a much lower coefficient of thermal expansion. As a consequence of the heating, the cantilever bows up (or 15 down) in a generally linear motion of input power to Z tip motion. The piezoresistive element 4010 is placed in stress, which changes its resistance.

The compensation element 4015, made of the same material as the sensor, contains substantial portions 20 of the element in an axis at right angles to the stress, and are thus not subject to the change in resistance due to the motion. However, both elements resistivity will change due to the thermal temperature change from the heating element, and proportionally to



the temperature. Thus the change due to temperature can be removed from the data returned from the sensor.

Each of the masks presented throughout this application are actual masks for making the devices.

5 The masks are negatives.

The servo lines are utilized in calibrating movement of the platform (fine tips) and media. The media and platform are first moved to an extreme position, the tips are set to sense, and then the  
10 platform and media are moved back from the extreme position until a first servo line is read by the fine tips. As the fine tips move across servo lines, an amount of force required for the movement mechanisms of the media and platform are calculated.

15

#### **XY ACTUATORS AND SPRINGS**

Various actuator and spring configurations are shown in Figure 3, and Figures 5 through 8. In Figure 3, also shown in Figure 2, a meander spring is  
20 formed with a sandwich of conductors and optional insulators. There may be as few as one conductor. When an electrostatic potential is applied to the conductor, electrostatic repulsion forces the leaves of

the spring apart, pushing the moving end 290 of the spring away from the fixed end 280.

Figure 5 shows a similar type of spring, which differs in that the length of each row of spring is of the same length. The fixed end is location 500 and the moving end location 510. This has the advantage over spring 3 in having higher compliance per area of spring, but the disadvantage of wasting the space in the triangle of region 520.

Figure 7 is the one embodiment of an actuator/spring for maximum motion with reasonable compliance in the axis at right angles to the actuation motion. This actuator is also formed from alternating conductors with differing potentials such as between fingers 700 and 710. The actuator is fixed at 720 and moves at end 710.

Figure 8 is an embodiment actuator/spring for moderate motion with high compliance in the axis at right angles to the actuation motion. This actuator is designed to maximize stiffness of bending in the Z plane, and when used with another identical spring/actuator on the opposite side of the platform, forms the major axis of stiffness in the Z plane for the platform. This actuator is also formed from

alternating conductors with differing potentials (pot 1, pot 2) running through fingers (830 and 840, for example). The electrostatic force pulling the structure 835 together is a summation of electrostatic  
5 forces between adjacent fingers. The actuator is fixed at 800 and moves at end 810.

All of the actuators may optionally contain an additional conductor which may be used either as a driver or as a capacitive sensor for sensing the  
10 position of the actuator. An example of the cross section of an embodiment is shown in Figure 14. Conductors 1400, 1410, and 1420 are sandwiched in between insulators 1430. Optionally there will also be insulator on the side walls. Conductors 1400 are set  
15 at one potential. Conductors 1410 and optionally 1420 at a different potential. Electrostatic potential will pull the conductor fingers 1440 towards 1450, likewise 1460 towards 1450, thus compressing the actuator. Conductor 1420 or 1410 may optionally be used as a  
20 capacitive sensor to determine the position of the actuator by sensing the varying capacitance formed by the varying distance between the conductors as the actuator expands and contracts.

It is important to note that in actuators in Figures 3, 5, and 7, the formation of the two sets of conductors formed at an axis some degree away from horizontal (in these cases 30 degrees) forms an improved (lower) compliance in the axis at right angles to the axis of actuation motion.

#### **ALTERNATE EMBODIMENT OF XYZ ACTUATORS AND TIPS**

An alternate embodiment of a cell is shown in Figure 11. This consists of a pair of X actuators 1100 and 1110, Y actuators 1120 and 1130, twelve Z actuators with tips 1140, and sets of connector conductors 1160-1190. Region 1195 is area etched out under the suspended structure.

#### **ALTERNATE ROTATING MEDIA INTEGRATED CIRCUIT**

An alternate version of the Nanochip is the Nanodisk and Nanodrive device shown in Figure 17. Here, sets of actuators 1700-1703 (shown in Figure 16) are arrayed around the rotating media Nanodisk 1710. Each actuator platform operates on a set of tracks which are shown within the bounds of the concentric circles in Figure 17.

By operating the radial positioners 1620 and 1630, individual tracks may be selected. Normally, only one of the 6 tips from each platform is operated at a time. In systems where the disk rotation speed is very slow, rotation speed compensation actuators 1600 and 1610 may not be needed. However, normally the disk media speed is much greater (0.1 to 1 m/sec) than the normal speed with which a conventional non-moving media scan is performed (0.03 m/sec).

For example, in Figure 17 the disk media might be 4 mm dia. In order to minimize the latency to any piece of data on this disk, the rotation speed should be at least 3600 rpm or 60 revs/sec, for maximum latency of 16 ms. The innermost and outermost useful tracks might be at 1.9mm and 0.3mm radius. The corresponding velocities would be 0.7 m/sec and .11 m/sec. The actuators 1600 and 1610 are used to apply a speed compensation, by applying a force to the moving platform in a direction the same as the rotation of the disk, causing the relative speed of the platform to the media to be reduced.

The tip is then operated in the same manner as described in the previous application, or in a manner described in this application with regard to different

types of tips and media. When the maximum travel of the compensator has been reached, the tips are retracted, the compensators moved to the opposite extreme position, and the process repeated.

5 In an alternate version, there are multiple tip assemblies arrayed around the disk equally spaced and multiple sets of tips designed to access the same tracks. This allows the access time to any location on the disk to be reduced by a factor n where n is the  
10 number of sets of tips for each track. Or the rotation speed may be slowed to the point where the rotation speed compensators are not needed. The number of tips also could be smaller near the hub of the disk, as the linear velocity is slower near the hub.

15

**ALTERNATE EMBODIMENT USING ARRAY OF ACTUATORS WITH ROW AND COLUMN CONTROLS AND INPUT/OUTPUT**

An alternate embodiment is shown in Figure 29. In  
20 the following, the use of row and column may be transposed. In this embodiment, a two dimensional array of actuators, each with single or multiple tips, are arrayed. The arrays are connected such that X and Y controls for each platform can be driven  
25 individually, by connecting one set of the pair of

lines to a common connection for each row, and the opposite of the pair to a common line for each row.

Alternately, drive electronics may be integrated for each platform. Eliminating the need for active  
5 electronics on the MARE greatly reduces the number of steps to fabricate the MARE, thus reducing the cost and time to manufacture. Although only one column may be driven at any instant, the inherent capacitance of the system, plus the inertia of the components, allows each  
10 section to be multiplexed. Alternately all platforms can be connected electrically to a common set of X and Y controls, with the disadvantage that feedback for each platform is not possible, thus reducing accuracy and thus bit density.

15 Groups of actuators along a column have a common Z drive connection (ZDcolm). Sets of controls along rows provide the other Z drive connection (ZDrown). Applying a large differential voltage between Zdcolm and ZDrown effectively enables the Z actuation of the  
20 intersecting row and column controls on the actuators. Alternately, if all actuators along a single column are enabled with one column drive and all row drives on, all Z actuators on that column will be enabled.

Each individual Z drive may have slightly different values to accommodate differing height controls.

Tips of the actuators are also connected in common in sets along rows. When used in tunneling or  
5 resistive mode, the data under tips along a column may be read out via the resistance between the tip and the substrate. So all tips under a column may be read or written simultaneously and individually.

In an alternate embodiment, the set of X and Y  
10 controls may be split into multiple banks, to allow simultaneous access to multiple blocks of data. The row and column arrangement may be maintained, or additional and separate sets of rows and columns for each bank provided.

15 In an alternate embodiment, the column enables are connected such that one "column" enable only enables one tip from each actuator platform, and the enable is spread over multiple platforms such that effectively a large number of tips are accessed simultaneously. The  
20 advantage of this embodiment is most pronounced when the Z actuators are used in an oscillating AFM mode, where the Z cantilevers are vibrating at a high frequency. This allows only one cantilever vibrating per platform to be operating, reducing problems



associated with mechanical coupling between cantilevers.

**PERFORMING A WRITE OPERATION ON APPARATUS FIG. 1**

5 To perform a write operation, a control voltage positioning signal is applied either through the I/O pads 10 or separate actuator control input pads. The control voltage is enabled for input by enabling input enable 20 and disabling output enable 30. Four (or three) sets of control voltages, one for each spring/actuator, generate a force which creates a motion of the springs/actuators and subsequently the suspended platform.

15 This motion is typically designed to first move the platform to a start scan position, nominally an extreme in X or Y. For this discussion, we will use extreme left in X for start position. The Y position will determine the track to be written. A control set is then applied to move the platform, nominally at 20 maximum acceleration, to get the platform up to the nominal scan speed (typically somewhat lower than maximum velocity). Once nominal velocity is achieved (for example,  $3 \times 10^{-2}$  m/sec), the tip actuator assemblies are instructed to raise the tip assemblies

towards the media surface. While in this mode, the tip is in a read mode, sensing track, sector, and data information.

When the correct track with optional sector  
5 position has been reached, as determined by the tip in read mode, the operation of the tip is switched to write mode. When in write mode, the tip bias voltage is alternated between a sense read mode, where the bias voltage is of a low enough value that no change is  
10 effected to the memory surface, and a write mode, where the bias voltage is of sufficient intensity to effect a change to the memory surface.

During the sense read mode state, the current between the tip and the memory is measured. If the  
15 current has increased, this indicates the tip is closer to the memory surface. Conversely, if the current drops, this indicates the tip is further from the memory surface. This information is processed by the computer and fed to the Z axis positioner to raise or  
20 lower the tip to maintain the height required by a particular memory technique described below. The current information in one embodiment is measured via a simple 2 CMOS transistor amplifier, with typical Beta of 50. In the current sensing mode, the tip is

first biased at a nominal input voltage such that the output voltage of the amplifier is in a mid-range between + and - supplies.

As the small current starts to flow, depending on the bias of the media, the output of the sense amplifier will begin to rise or fall. This indicates the tip is approaching the media. In an alternate media embodiment, the information is stored as an electronic charge. When the tip approaches the media, the charge is transferred to the tip capacitance. This charge is amplified by the sense amplifier transistors and is indicated by a sudden change in the output voltage of the amplifier, indicating the charge has been transferred to the tip and that the tip is in proximity to the media.

The data portion of the memory is written with an alternating control voltage such that the data pattern will never match a track or sector pattern, and additionally always alternates from one state to another within several data bit states. An example of such a pattern form is non-return to zero, referred to as NRZ. This form also has the advantage of supplying self clocking information when in read mode (the NRZ format has transitions at regular intervals which is

utilized for clocking). Also, the state is guaranteed to return to a read sense state often enough to obtain necessary surface height information.

In the capacitive charge storage media method, the above method destroys the data during read, thus requires a subsequent re-write.

In an alternate embodiment, data is stored as an electronic charge on a nitride-oxide-substrate (or NOS) structure. In this embodiment, charge is written by positioning the tip near or on the media (nitride) surface. A voltage pulse of sufficient amplitude to tunnel through the nitride is applied to the tip. A subsequent charge is then stored on the oxide, which then forms a depletion layer in the substrate region. This depletion region modifies the effective capacitance of the area below the tip in effect lowering the capacitance. To read this change in capacitance, a sensitive capacitance measuring circuit is employed. This embodiment has the advantage of not requiring that data bits be re-written after each read.

Many of the media forms can be improved with an additional set of processing steps which effectively alter the shape of the media surface from a continuous

sheet to a 2 dimensional array of discrete, small regions. This can be created by use of interference patterns from a laser beam which is reflected back on itself, which effectively creates a grid of spacing  
5  $\frac{1}{2}$  the wavelength of the laser source. In one axis this forms spaced lines. Formed at right angles to the first set a grid pattern is formed. This can be used to expose a thin resist, which can then be used to subsequently pattern the media. Use of excimer lasers  
10 with wavelengths of 157 nm yields a pattern of 78 nm spacing as an example.

Alternately, this can be achieved by first depositing a thin layer of a metal such as gold on the media surface. The media is then slowly heated to  
15 cause the thin metal to form beaded regions with no metal in between the beads. These beads then effectively form a mask. An anisotropic etch, typically with reactive ion etching (RIE) or similar dry etching technique, removes the material in the open  
20 areas between the beads.

In an alternate media embodiment, the media consists of structures forming quantum dots. These may be formed using multiple quantum well (MQW) techniques. The media is written by applying a voltage pulse

sufficient to change the electron state energy in the trapped quantum well regions.

#### MANUFACTURING TECHNIQUES

5           The apparatus described herein are primarily designed to be fabricated with semiconductor processing techniques. A typical apparatus would be first fabricated with a CMOS or BiCMOS fabrication process. Then, the wafer or die would be placed in a  
10   silicon etchant and released by a post process etch using wet chemicals such as KOH (potassium hydroxide) or TMAH (tetra-methyl ammonium hydroxide) or dry etching using RIE or plasma etching in an isotropic mode such that etching proceeds under the moving  
15   structures.

          Alternately, the devices can be released by etching in a vapor of XeF<sub>2</sub> (xenon difluoride) or RIE in SF<sub>6</sub> (sulfur hexafluoride). Active electronics would be protected by glass or oxide layers. The tips may be  
20   fashioned from the single crystal Si in the substrate, or from a low temperature deposited silicon, then protected by a thin coating impervious to the final release etchant. In another alternative, the tips may be fabricated by FIB techniques.

However, in the past, most Micro Electric Mechanical Systems (MEMS) structures have been fabricated with polysilicon or single crystal silicon. These have a high Young's modulus and tend to have  
5 lower residual biases in the thin film layers than materials such as oxide and aluminum. Most of the spring structures described herein may be fabricated from silicon or polysilicon, given oxide completely surrounding all structures, and using a final silicon  
10 etch.

However, materials such as aluminum and oxide for the MEMS structures, as these have lower Young's modulus by a wide margin ( $69 \times 10^9$  instead of  $170 \times 10^9$ ), aluminum has much lower resistance, and the  
15 micromechanical structures can be fabricated out of the same steps which are normally used for the metal interconnects and intermetal dielectrics. Unfortunately, most processes tend to leave quite large residual biases in these materials. But fortunately,  
20 the direction of the biases for different layers tend to be different. By careful tailoring of multi-layer films and their biases, and one or more additional process steps, the sum of the residual stresses can be reduced to a very low value.

Figure 21 shows 3 examples of multi-layer films. Figure 21A shows a two layer multi-layer film. If one layer has positive stress  $T+$  and the other layer has negative stress  $T-$ , and  $T+ + T- > 0$ , by thinning  $T+$ ,  
5 the total stress can be reduced to near zero.

If one layer has negative stress  $T-$  and the other layer has positive stress  $T+$ , and  $T+ + T- < 0$ , by thinning  $T+$ , the total stress can be reduced to near zero. The thinning may be performed isotropically or  
10 anisotropically, depending on which layers need to be affected. With 3 or more layer films, such as in Figures 21B and 21C, if the sum of the positive stress films is  $TN+$ , and the sum of the negative stress films is  $TN-$ , and  $TN+ + TN- > 0$ , by thinning  $TN+$  the sum of  
15 stresses can be reduced. If the sum of the positive stress films is  $TN+$ , and the sum of the negative stress films is  $TN-$ , and  $TN+ + TN- < 0$ , by thinning  $TN-$  the sum of stresses can be reduced.

As an example, typically 2110, 2120, 2140, 2160,  
20 2180 would be oxide, 2100, 2130, 2150, 2170 would be aluminum. By etching the oxide with HF or Buffered HF, the results of thinning would look like 22a-c. Alternately, the total stress bias may be reduced by a post annealing step.



#### COMPENSATION FOR SURFACE DEFECTS

The present invention may use any of the techniques previously described in the previous patent application for compensating for surface defects.

5 Additionally, by virtue of the large number of tips, the media may be scanned in a much shorter time than might normally be available in a single head system.

#### FINE TIP SHARPENING

10 Similarly, fine tip sharpening techniques, such as those described in *Rust et al.*, U.S. patent 5,453,970, may additionally be used to keep the fine tips clear of debris.

#### 15 MEDIA

Any one of the media described in the previous application may be used with the current apparatus when used in the current mode of operating the tip. In one embodiment of the re-writable media, a charge is

20 stored on an insulator above a conductor. This is preferably an insulator with a high dielectric coefficient, and extremely low leakage. Examples of dielectrics are silicon dioxide, titanium dioxide, and piezoelectric materials such as PZT. Alternately the

charge may be stored in a region below the surface, such as with NOS materials such as silicon nitride over silicon oxide on silicon substrate.

In an alternate capacitive media such as NOS, an  
5 alternate read technique is to use a capacitive bridge amplifier which senses the small difference in capacitance on one of the legs of a bridge (the capacitor being the NOS data bit). This has the advantage of not destroying the data bit during read.  
10 Unfortunately, the sense electronics are considerably more complicated.

#### **METHOD FOR DATA COMPRESSION**

Figure 27 shows a typical configuration for the  
15 orientation of stored bits. Figure 28 shows a honeycomb data storage configuration which provides a 15% storage improvement. The area of a bit changes from:  $D$  - diameter of bit rectangular array area:  $D^2$   
honeycomb array area:  $D^2 \tan(\pi/3)/2$  or approx.  $.86D^2$   
20 The spacing from center to center remains the same, so Gaussian distribution bit shapes all can benefit from this compaction method.

**MARE AS LITHOGRAPHY APPARATUS**

The current contenders for production scale lithography for the under .25u regime are X-ray - costly and still limited to perhaps .1u, and ion beam  
5 projection - a still experimental system again with probable limits of .1u. Both of these systems also are for exposure only -- they have no inherent metrology capability for analyzing the results. The MARE portion of the Nanochip is itself a high speed  
10 lithography instrument with up to 10 nm resolution. The Nanochips inherent parallelism will allow the patterning of a 6" wafer in approx. 8 minutes (5x5cm Nanochip, 1Mhz/tip data rate, 30nm line width).

In addition, the Nanochip lithography instrument  
15 will allow the patterning to be checked for accuracy by the same instrument. This can be used to identify particle defects and used as a gauge to eliminate unnecessary processing. Also, the data for the mask remains digitally represented - there is no need for an  
20 intermediate mask to be generated.

Additionally, by scanning the tip in the presence of a bistable gas or liquid medium which changes to a solid state when in the field of the voltage/current spike produced by the tip region, materials may be

deposited on a surface a layer at a time and built up to construct three dimensional geometries. STMs have been used to pattern photoresist and form very fine geometries (10nm lines), additionally silicon dioxide  
5 has been formed in silicon, which can then be used as a mask for additional semiconductor processing steps.

The MARE and molecular media technologies in this application will also be a primary enabling force for flat-panel display fabrication for field emission  
10 displays. The diamond media forms donut shaped hillocks of extremely fine dimension. These can be used as field emitters for field-emission based flat panel displays.

In one embodiment, the media is constructed of a  
15 base from any material having charge storage capability. For example, any material that stores electrons when a charge is applied. The charge storage capabilities are then enhanced by augmentation of grain boundaries of the media material. This augmentation is  
20 performed by applying material coating (texture coating, PMMA, for example) to the surface of the media material, and then removing the coating. Pit markings remain that augment the grain boundaries of the media material, and enhance the charge storage capabilities

of the media. Examples of the augmented grain boundaries can be seen in the photographs of Figs. 42A-42E.

Portions of the present invention may be  
5 conveniently implemented using a conventional general purpose or a specialized digital computer or microprocessor programmed according to the teachings of the present disclosure, as will be apparent to those skilled in the computer art.

10 Appropriate software coding can readily be prepared by skilled programmers based on the teachings of the present disclosure, as will be apparent to those skilled in the software art. Portions of the invention may also be implemented by the preparation of  
15 application specific integrated circuits or by interconnecting an appropriate network of conventional component circuits, as will be readily apparent to those skilled in the art.

The present invention includes a computer program  
20 product which is a storage medium (media) having instructions stored thereon/in which can be used to program a computer to perform any of the processes of the present invention.

Stored on any one of the computer readable medium (media), the present invention includes software for controlling both the hardware of the general purpose/specialized computer or microprocessor, and for  
5 enabling the computer or microprocessor to interact with a human user or other mechanism utilizing the results of the present invention. Such software may include, but is not limited to, device drivers, operating systems, and user applications. Ultimately,  
10 such computer readable media further includes software supporting and controlling devices and mechanisms according to the present invention, as described herein.

Obviously, numerous modifications and variations  
15 of the present invention are possible in light of the above teachings.